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Impact–triggered breakup of comet C/1999 S4 (LINEAR): Identification of the closest intersecting orbits of other small bodies with its orbit

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Abstract. As we are still not certain of the causes of the splitting of comet C/1999 S4 (LINEAR), we attempt to explain the initiation and/or triggering of the breakup of the nucleus of this comet by impact–induced events from possible larger debris or a debris cloud dispersed around the orbits of known asteroids. A computer search showed that Comet C/1999 S4 (LINEAR) crossed the orbits of seven known asteroids from December 1999 to March 2000. Impact–induced activity may have initiated or contributed to the breakup process of this comet in late 1999 or early 2000 creating the observed fragments in July and August 2000.

Key words. comets: individual: C/1999 S4 (LINEAR) – meteors, meteoroids – minor planets, asteroids – Solar system: general

1. Introduction

Disintegration of cometary nuclei is an enigmatic phenomenon. It is important to observe them and to understand the physical nature of this process, moreover, it is a unique opportunity to reveal the internal structure of cometary nuclei from remote observations.

Nightly observations made from July 23, 2000 showed what appears to be the complete disruption of the nucleus of comet C/1999 S4 (LINEAR). The central condensation brightness decreased by a factor of about 3 between the two nights of observation on July 23–24 (Kidger 2000). This is a large photometric outburst which may be associated with the disruption event. Licandro et al. (2000), Filippenko & Chornock (2000) have also reported the peculiarity of the near-nucleus coma morphology and their data suggest a major event occured in the nucleus of the comet. Hubble Space Telescope (HST) and Very Large Telescope (VLT) imaging observations taken in early August revealed about a dozen active fragments with a diameter of 100 m or smaller and with rapid variability in the activity levels (Weaver et al. 2000a, 2000b). Moreover, the early HST images of the comet show a dramatic increase in activity on July 5, one day later the activity levels were decreasing and were about 3 times lower for the final observations (Weaver et al. 2000c).

We are still far from the complete understanding of the puzzling breakup event of this comet and we recall here some observational results and possible interpretations. A preliminary analysis by Sekanina (2000) suggested that the breakup event may have begun as early as July 23.6 UT and unusually large nongravitational forces were reported (Marsden 2000). Observations made in the near-infrared show that the C/1999 S4 was an absolutely well-behaved comet on June 17–19, 2000 (Peschke et al. 2000). The flat dust production is consistent with the scenario that C/1999 S4 is both a dynamically new comet and experienced an outburst with very low outflow velocities at large heliocentric distance, moreover, the measured gas and dust production peaked during an apparent outburst centered on June 11 (Farnham et al. 2000). Schleicher (2000) has reported a remarkable scenario to explain his resulted narrowband photometric observations made on 1999 December 5, 28, and 30: the apparent decrease in dust production implies either an earlier outburst or significant variability due to the rotation of the nucleus. There are several other outbursts of this comet and it seems to be that the final disruption event was just one of a long series of individual outbursts. This raises the question as to whether or not collisional events many months before perihelion could act as a triggering for the whole series of photometric and fragmentation events that were observed later. Hereafter we confine the idea of impact–induced activity suggesting an idea on a triggering mechanism which weakened the cometary nucleus leading to the breakup event. This paper lists the closest known asteroidal orbit from which the asteroidal debris projectiles

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Table 1. Orbits having the closest known approach distance to the orbit of C/1999 S4 (LINEAR)

	Parent body			C/1999 S4 (LINEAR) at the crossing point							
#	Object	Orbit class	H (mag)	t_{cross} (UT)	Δt (day)	r (AU)	L (°)	B (°)	v_{rel} ($\mathrm{km\,s^{-1}}$)	γ (°)	d_{min} (10^3 km)
*2	1998 FS53	MB	13.86	1999 Dec. 14.59	−218.41	3.459	59.43	13.41	29.84	104.07	6.7
*3	2000 QY87	MB	13.97	2000 Jan. 10.47	−191.53	3.144	56.67	14.80	34.96	118.69	25.3
4	2382 Nonie	MB	11.40	2001 Mar. 01.49	224.49	3.386	168.18	−30.51	34.09	132.17	27.4
*5	17644 1996 TW8	MB	12.90	2000 Mar. 01.22	−140.78	2.517	49.37	18.23	39.90	120.25	27.5
6	C/1781 M1	l-p	7.90	2000 Aug. 08.05	19.05	0.806	265.82	1.56	51.15	66.05	27.9
*7	1998 QW41	MB	13.86	2000 Feb. 10.43	−160.57	2.767	52.64	16.74	38.91	122.69	30.6
8	1997 CD17	Ap	27.47	2000 Aug. 30.09	41.09	1.016	236.23	−15.02	67.69	136.64	43.8
*9	1999 XR172	MB	13.63	2000 Jan. 22.28	−179.72	3.002	55.26	15.49	35.24	112.95	52.5
*10	1998 SB57	MB	14.82	1999 Dec. 14.46	−218.54	3.460	59.44	13.40	33.10	122.39	73.9
*11	2134 Dennispalm	MB	11.50	2000 Mar. 13.44	−128.56	2.360	46.96	19.27	36.78	99.61	90.6

Orbit class: MB – Main Belt asteroid, Ap – Apollo asteroid, l–p – long–period comet.
H: absolute magnitude in the two-parameter magnitude system (Bowell et al. 1989); for the comet H_0 is given.
t_{cross}: time of the crossing point passage.
$\Delta t = t_{\mathrm{cross}} - t_{\mathrm{ref}}$: time interval between the crossing and a reference date of t_{ref} 2000 July 20.0 UT.
*: refers that passage the crossing point is before the reference date.
r, L, B: heliocentric ecliptic coordinates, v_{rel}: relative orbital velocity.
γ: angle between the orbital velocitiy vectors at the crossing point, d_{min}: minimum distance of orbits.

could have collided with Comet C/1999 S4 (LINEAR) to trigger the breakup process. A number of splitting mechanisms have already been proposed and the topic of split comets and outburst mechanisms has been extensively reviewed (Hughes 1991a,b; Sekanina 1968, 1982, 1997; Chen & Jewitt 1994). The idea that meteoroid impact–induced activity and/or disintegration of a cometary nucleus is one of the explanations of certain types of outbursts and breakup events. More recently a correlation between enhanced episodic outgassing and the passage of the comets through well-known meteor streams was investigated by Matese & Whitman (1994). Very recently the impact-generated activity period of the asteroid 7968 Elst–Pizarro in 1996 was studied by Toth (2000) and the most probable asteroidal parent body of the impactors was identified.

2. Possible impactor parent bodies

To find the orbits of the possible parent bodies of impactors a computer search method was used. It had already been applied earlier revealing the possible parent body of the impactors to generate a probable impact–induced activity of the 7968 Elst–Pizarro (Toth 2000). The minimum distances between the orbits of C/1999 S4 (LINEAR) and all other small bodies were calculated. The known asteroidal (Bowell's data), cometary (Marsden & Williams 1999), and meteor stream orbits (Kronk's data) were considered as far as is possible in a computer search for the probable parent bodies of the impactors. The objects were sorted according to the value of the determined minimum distance and the objects from a few 10^3 km to some 10^4 km from the orbit of C/1999 S4 (LINEAR) were selected (Table 1). This distance limitation was chosen because of the possible uncertainties in the orbital elements and the expectably spatially widened debris stream extension. Studies of the spatial distribution of orbitally evolved collisional debris show that the debris cloud is widened due to the dispersion of the orbital elements of its components as it has been observed by the IRAS satellite (cf. Sykes & Greenberg 1986). Seven known Main Belt asteroids are within some 10^4 km of the orbit of C/1999 S4 (LINEAR) for which this comet reached the points of the closest approach distance before the first observations of the splitting on 23/24 July 2000 (Kidger 2000). A long–period comet C/1781 M1 (Mechain), a Main Belt asteroid 2382 Nonie, and an Apollo asteroid (1997 CD17) were also found with close minimum distances but the C/1999 S4 had not reached the crossing points with these orbits before the observed splitting.

H magnitudes of the asteroids, listed in Table 1, are given in the two-parameter magnitude system (Bowell et al. 1989). A diameter estimation can be done applying the empirical relation between H and the geometric albedo (cf. Harris 1998); e.g.: adopting a value of geometric albedo of 0.15 and $H = 13.8$ mag (1999 FS53), a diameter of 6 km is estimated. Adopting smaller values for the geometric albedo increase the size, i.e. these main belt asteroids are in the ∼5–20 km diameter class. These parent asteroids are able to produce an associated debris swarm or larger meteoroids from their large ejecta fragments (Asphaug 1994), which can spread along the orbits of the parent asteroids because of their initial collision related ejection velocity, as well as both by gravitational and Yarkovski–O'Keefe–Radzievski–Paddack (YORP) effect perturbations.

Arranging the seven selected objects according to the minimum distance they are as follows: 1998 FS53, 2000 QY87, 1996 TW8, 1998 QW41, 1999 XR172, 1998 SB57, and 2134 Dennispalm. These are marked by asterisk in Table 1. Comet C/1999 S4 (LINEAR) crossed the minimum orbital distance points of these objects between December 1999 and March 2000 at about 3.46 and 2.36 AU heliocentric distance, respectively, before its perihelion passage on 26 July 2000. Each crossing point is located at a distance of $\sim$0.8 AU above ecliptic plane. At the minimum separation points of these orbits the actual relative orbital velocities range between 29 and 39 km s^{-1} and the angle between the heliocentric orbital velocity vectors are in the range of 99°–122°. If these velocities are the impact velocities of the meteoroids, the possible impacts on the cometary nucleus could be high-velocity collision events.

How could the collisional events act as a trigger for the whole series of activity and fragmentation events many months before perihelion? One possibility is that an initial impact started a process of slow fragmentation of the nucleus by loosening and eventual separation of individual blocks of material and that each subsequent photometric event was due to the separation of a new block. Indeed, many months before the perihelion of C/1999 S4 the following two asteroidal orbits were crossed by the comet both on the same day, i.e. on 14 December 1999: 1998 FS53 and 1998 SB57. This date is bracketed by Schleicher's December 1999 observations. Moreover, other orbits were crossed from January to March 2000 in chronologic order: 2000 QY87 (Jan. 10), 1999 XR172 (Jan. 22), 1998 QW41 (Feb. 10), 17644 1996 TW8 (Mar. 1), and 2134 Dennispalm (Mar. 13) (Table 1).

3. Effects of the meteoroids

A single passage of a comet through the most dense region of a meteor stream would produce, on average, only a minor peppering contamination on the surface of the nucleus. However, it must be emphasized that the 1–1000 kg meteoroids that certainly exist in a debris cloud are much more likely to be found at the dense core of the meteoroid streams. A small crater does not by itself cause a split (cf. results by Hughes 1991b, applying a scaling law to estimate the crater diameter created on the surface of Comet Halley's nucleus). But if the exposure of fresh icy volatiles and dust that the cratering event reveals is cometographically placed such that the incident solar irradiation may cause such an increase in the gas sublimation rate that it triggers the breakup of the fragile nucleus. A collision with a 1000 kg meteoroid would form a crater of a volume somewhat greater than 150 m^3 (Babadzhanov et al. 1991).

The results by Matese & Whitman (1994) are interpretable as the catalytic increase in volatility as the impacting meteoroids penetrate any surviving mantle and probe the icy subsurface regions. How large is the effect of high-velocity meteoroids impacting and penetrating into the surface of an icy target body? A laboratory experiment-based model allows one to estimate a crater depth L depending on the projectile length d, its bulk density ρ at different impact velocities V (cf. Eq. (1) of Cintala 1981). Projectile meteoroid bulk densities have already been extensively studied both for cometary and asteroidal dust grains (Lamy et al. 1987; Ellis & Neff 1991; Wilck & Mann 1996) so we use their data in our calculations. The realistic porous, fluffy cometary material bulk densities range from $\sim$0.3 g cm^{-3} to 1–2 g cm^{-3} and the asteroidal dust density varies between 3–4 g cm^{-3}. Since the $L \propto \rho^{1.045}\ V^{0.349}$ the asteroidal meteoroids can excavate deeper craters, holes or grooves than cometary meteoroids at the same value of impact velocities, therefore the crater volume depends on the projectile bulk densities rather than the impact velocity. A size range was selected between 1 micron and 1 cm. A spherical projectile with a radius of 1 cm and a bulk denstity of 4.0 g cm^{-3} it has a mass of 16 grams. Projectiles in this mass range can penetrate into the nucleus to a depth of a few decimeters or meters with all the impact velocities chosen, but the micron sized projectiles contaminate the surface only to a depth of 0.01 cm. So, gram-sized meteoroids can create significant physical effects extending a few meters into the surface. At this point we recall here the conclusions by Matese & Whitman (1994) that the impacts are associated with shock waves and surface heating effects, which should produce a substantial perturbation to the pre-existing pressure-weakened substrate. Moreover, the stress-weakened subsurface regions will be vulnerable to small external perturbations resulting from the high-energy impacts. The scaling laws for the resulting craters excavated in originally low-temperature ice were investigated in more detail by Lange & Ahrens (1987). They concluded that greater ejecta volume is created by cratering in ice compared to the cratering in silicate targets. In addition, the impact heating of water-ice targets has significant effect (Cintala 1980). If amorphous water ice exists in comets (Prialnik & Bar-Nun 1987) and the impact heat wave penetrate deeply into the nucleus, the amorphous ice begins to crystallize and this exothermal process can induce an outgassing activity (Matese & Whitman 1994).

The detailed modeling of the impact processes is out of the scope of this short communication and the above described effects of high velocity (30–40 km s^{-1}) small projectiles are only an illustration for those that can cause significant damage to the target nucleus surface such as the continous enhancing the outgassing and driving away of the particulate material. In this case do not need the occurence of huge discontinuities in the activity curves. The effects of the larger meteoroids are obviously much more significant. For the purpose of the further investigation we quote here a new result. Very recently a new regime of impact physics in modeling the impact of various density and shape projectiles on comets as porous icy–dusty bodies and asteroids was found by

O'Keefe et al. (2000). Their modeling results agree with laboratory measurements of impacts on various porous low density materials. They studied the characteristics and scaling laws of the cratering processes. The resulting crater cavity shape can be bulbous or carrot shaped as opposed to bowl-shaped of flat floored in the case of simple and complex planetary craters. In the case of Comet C/1999 S4 (LINEAR) this means that either a larger amount of fresh cometary nucleus material can be exposed by the solar irradiation or a larger material fraction can be excavated and removed from the nucleus near-surface interior, or both. So, it is possible that a "natural Deep Impact event" occurred on the surface of C/1999 S4 in late 1999 or early 2000. Moreover, an impact into a rubble pile should not produce and propogate large shock wave, since such propogation requires an intact solid body. Rather, an impact into a rubble pile may spend its energy knocking off and spinning up small monolithic fragments (Asphaug & Scheeres 1999; Whiteley et al. 2000). An impact of a larger projectile can change the rotational state of the target body both by a off-mass-center collision and the repulsive force of the ejected, excavated and even activated cometary material.

4. Conclusions

We have attempted to explain the initiation or triggering of the breakup of the nucleus of this comet by impact–induced events after collision with possible larger debris or debris cloud dispersed around orbits of the known asteroids. A computer search showed that Comet C/1999 S4 (LINEAR) crossed the orbits of seven known asteroids from December 1999 to March 2000. The consecutive passages through the orbits have relative encounter velocities ranging from 29 to 39 km s^{-1} which could lead to high velocity collision events with the possible asteroidal debris material spreaded over the orbits of these parent bodies. One possible explanation of the observations made in December 1999 is an outburst (Schleicher 2000). Seven asteroidal orbits were crossed by the comet from December 1999 to March 2000. Two of these are bracketed by the Schleicher's December 1999 observations (Schleicher 2000).

Apart from the obviously larger meteoroids with masses of kilogram or metric tons, smaller meteoroids have also surface damaging effects at high impact velocities. The larger high velocity projectiles can change the rotational parameters of the nucleus: spinning it up and/or exciting the rotation. The larger impactors can cause spinning up, moreover, they can excavate a huge amount of material supporting the rotational breakup, as well as generating large non-gravitational effects.

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References

Asphaug, E. 1994, Meteoritics 29, 440
Asphaug, E., & Scheeres, D. J. 1999, Icarus, 139, 383
Babadzhanov, P. B., Wu, Z., Williams, I. P., & Hughes, D. W. 1991, MNRAS, 253, 69
Bowell, E. L. G., Hapke, B., Domingue, D., et al. 1989, in Asteroids, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Univ. of Arizona Press, Tucson, AZ), 524
Chen, J., & Jewitt, D. 1994, Icarus, 108, 265
Cintala, M. J. 1980, LPI, 11, 140
Cintala, M. J. 1981, Nature, 291, 134
Ellis, T. A., & Neff, J. S. 1991, Icarus, 91, 280
Farnham, T. L., Schleicher, D. G., Woodney, L. M., et al. 2000, BAAS, 32, 1075
Filippenko, A. V., & Chornok, R. 2000, IAUC Circ., 7468
Harris, A. W. 1998, Icarus, 131, 291
Hughes, D. W. 1991a, Possible mechanisms for cometary outbursts, in Comets in the Post-Halley Era, ed. R. L. Newburn, M. Neugebauer, & J. Rahe, Astrophys. Space Sci. Libr., 167 (Kluwer Academic, Dordrecht), 825
Hughes, D. W. 1991b, MNRAS, 251, 26p
Kidger, M. 2000, IAU Circ., 7467
Lamy, P. L., Grün, E., & Perrin, J. M. 1987, A&A, 187, 767
Lange, M., & Ahrens, T. J. 1987, Icarus, 69, 506
Licandro, J., Tessicini, G., & Perez, I. 2000, IAU Circ., 7468
Marsden, B. G., & Williams, G. V. 1999, Catalogue of Cometary Orbits, 13th ed., IAU CBAT, Minor Planet Center, SAO, Cambridge, MA
Marsden, B. G. 2000, MPEC 2000–O07
Matese, J. J., & Whitman, P. G. 1994, Icarus, 109, 258
O'Keefe, J. D., Stewart, S. T., & Ahrens, T. J. 2000, BAAS, 32, 999
Peschke, S. B., Lisse, C. M., Fernandez, Y. R., et al. 2000, BAAS, 32, 1061
Prialnik, D., & Bar-Nun, A. 1987, ApJ, 313, 893
Schleicher, D. G. 2000, IAU Circ., 7342
Sekanina, Z. 1968, BAICz, 19, 63
Sekanina, Z. 1982, The problem of split comets in review, in Comets, ed. L. L. Wilkening, Space Science Series (Univ. of Arizona Press, Tucson), 251
Sekanina, Z. 1997, A&A, 318, L5
Sekanina, Z. 2000, IAU Circ., 7471
Sykes, M. V., & Greenberg, R. 1986, Icarus, 65, 51
Toth, I. 2000, A&A, 360, 375
Weaver, H. A., West, R., A'Hearn, M. F., et al. 2000a, IAU Circ., 7476
Weaver, H. A., West, R., A'Hearn, M. F., et al. 2000b, BAAS, 32, 1061
Weaver, H. A., HST ToO team, 2000c, IAU Circ., 7461
Whiteley, R., Tholen, D. J., & Hergenrother, C. W. 2000, BAAS, 32, 1003
Wilck, M., & Mann I. 1996, Planet. Space Sci., 44, 493